CHAPTER 6
Economic Models of Potential U.S. Offshore Aquaculture Operations

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This chapter provides a quantitative assessment of the economic feasibility of offshore aquaculture using a bio-economic model of firm-level investment and production.

Introduction

To evaluate the economic potential of offshore aquaculture, interactions among various economic and biological factors in a specific production process (species, technology, and location, for example) are modeled. Typically, a firm-level investment-production model includes revenue from fish sales, different cost components, and a biological growth function. The total cost of a specific technology consists of fixed and variable components. Fixed cost (for example, construction cost) is "sunk cost" once an investment has been made. Variable cost (such as feed, energy, and labor) may be controlled in future operations. Production may be optimized to improve the economic efficiency of a specific system.[1] Suppose revenue and cost projections for an open-ocean aquaculture project are accurate and there are no risks. A firm's investment decisions can be made according to the traditional NPV (net present value) rule: invest when the value of the project is at least as large as the investment costs (NPV ≥ 0).

This chapter provides a quantitative assessment of the economic feasibility of offshore aquaculture using a bio-economic model of firm-level investment and production. We develop case studies of offshore productions of Atlantic cod and salmon, respectively. The production technologies examined are large, offshore cage farms with a high level of automation.[2]

The Model

Our model assumes that the offshore grow-out operation will produce a fixed amount of fish each month, following pre-determined stocking and harvesting schedules.[3] The model simulates fish growth and projects financial flows for each month in a 15-year period. It calculates project NPV, the amount of up front investment required, and different cost components.

The model may take into account seasonal variability in the price of fish landings as well as the effect of water temperature on fish growth rates. It allows for comparison of different species at alternate grow-out sites, based on their biological and physical characteristics (Kite-Powell et al., 2003). Several economic, biological, and environmental variables (such as price, mortality, and water temperature) may be specified as stochastic to

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[1] For example, the biomass growth rate may be controlled through feeding rate and changes in density (e.g., stocking rate, survival/culling) (see Allen et al., 1984; Arnason, 1992).

[2] For an introduction to cage aquaculture, see Beveridge (2004).

[3] A different version of the model allows the optimization over stocking time and number of fish for each harvest month (see Kite-Powell et al. 2003).

capture random effects in fish growth and revenue from sales. For a given set of stochastic variables, the model calculates both the mean and the variance of project NPV.

Fish Growth

To ensure year-round fish yield, a certain number of fingerlings are stocked each month. For a particular cohort, fish growth may be modeled using the Beverton-Holt approach (Ricker, 1975), as follows:

$$x(\tau) = n(\tau)w(\tau) \tag{1}$$

where n is the number of fish in thousands and w is the weight of a fish in grams. In discrete time (τ = month) and without intervention,

$$n(\tau) = n(\tau - 1)(1 - m) \tag{2}$$

where m is the mortality rate (Allen et al., 1984), the number of fish will decrease while weight grows.

The growth rate of individual fish weight (w) in discrete time is

$$w(\tau) = w(\tau - 1) + g(\tau - 1) \tag{3}$$

where g is the weight growth function of an individual fish.

The feed conversion ratio (FCR) is defined as:

$$s(\tau) = \frac{f_0(\tau)}{g(\tau)} \tag{4}$$

where s is the FCR and f_0 is the quantity of feed per fish. Thus, the total feed quantity in kilograms (kg) at τ is

$$f(\tau) = f_0(\tau)n(\tau) = s(\tau)g(\tau)n(\tau) \tag{5}$$

Revenue from Fish Sales

For specific stocking and harvesting schedules, the model calculates the financial performance of the grow-out operation month by month over 15 years to determine projected cash flows. For an individual aquaculture farm, price is exogenous. We model dockside price as a function of fish size and time of year. With total harvest fish biomass at harvest time $x(T)$ in kg and market price (p) in \$/kg, the gross revenue from the sale of a cohort is

$$R(t) = p[w(T), t]\,x(T) \tag{6}$$

where t equals time over the study period [t = 1, 2, …, 180 (month)].[4]

Costs of Investment and Production

Total cost includes expenditures on cages, a boat, fingerlings, feed, and shore-based operations (e.g., administration and marketing). In the model, we assume a sequential cage installation schedule. For cod and salmon, the grow-out period is two years. There are 24 cohorts. Thus, for each of the first 24 months, there is one new cage added to the farm. The investment cost of each cage is

$$c_k(t) = v(acq + inst) + efix \qquad t = 1,2,\ldots,24 \tag{7}$$

[4] In the model, we specify stocking and harvesting schedules within this time frame. For example, Cohorts 1 is initially stocked at t = 1 (τ = 1), harvested at t = 24 (τ = T), and re-stocked at t = 25 (τ = 1). Note that $R(t)$ = 0 for t = 1 – 23.

where c_k is the cost of each cage in \$, v is the cage volume in m^3, *acq* is the cage acquisition cost in \$/m^3, *inst* is the cage mooring and installation cost in \$/m^3, and *efix* is the fixed cost associated with environmental compliance in \$/cage.

The installation cost is a function of water depth in meters (*wd*):

$$inst = 2 + 0.02wd \tag{8}$$

For cage maintenance in subsequent months, the maintenance cost is

$$c_m(t) = v \cdot cn(t) \cdot cm(t)/12 + evar(t) \qquad t = 25,26,...,180 \tag{9}$$

where *cn* is the number of cages in the farm, *cm* is the cage operating and maintenance cost in \$/m^3/year, and *evar* is the variable cost of environmental compliance in \$/month.

Each month, feed and fingerlings are transported to the farm and harvest is transported back to shore by boat. Aggregating cage-level feed quantity [$f(\tau)$ from (5)], we have the farm-level monthly feed quantity (*fq*) in kg:

$$fq(t) = \sum_{\tau=1}^{cn(t)} f(\tau) \tag{10}$$

For each month, the quantity of fingerling and water transported for stocking (*sq*) in kg is

$$sq(t) = stock \cdot sg \cdot \varphi \tag{11}$$

where *stock* [= $n(0)$] is the number of fingerlings in thousands, *sg* is the fingerling weight in gram/fish, and φ is the ratio of water weight to fingerling weight during transport to farm.

For each month, the total number of round trips is calculated as either the number of trips necessary for transporting harvest from the farm or the number of trips needed for transporting feed and fingerlings to the farm, whichever is greater.

$$nr(t) = max\{ x(T)/ld, [fq(t) + sq(t)]/ld \} \tag{12}$$

where $x(T)$ is the fish harvest in kg, *ld* is the boat payload in kg, *fq* is the feed quantity in kg, *sq* is the quantity of fingerlings in kg; *nr* is rounded to the nearest greater integer.

Since one vessel can transport a larger volume of cargoes by making more trips in a day if the distance to shore is short, the number of vessels needed for a given cargo volume is affected by distance. To estimate the number of vessels needed for the cargo volume, we first estimate the time for a round-trip (*h*):

$$h = 2d / spd + z_l + z_u \tag{13}$$

where *d* is the distance and *spd* is the average speed of the vessel in km per hour. The round-trip time is extended by adding the time for loading (z_l) and unloading (z_u).

The number of trips a vessel can make in a day is estimated as

$$nd = h_m / h \tag{14}$$

where h_m is the number of hours per day the boat is operational; *nd* is rounded to the nearest lower integer. The number of trips a vessel can make in a month is

$$nm = d_m \cdot nd \tag{15}$$

where d_m is the number of days per month the boat is operational. Thus, the number of vessels required for a specific month is:

$$bn(t) = nr(t) / nm \tag{16}$$

where *nr(t)* and *nm* are defined in (12) and (15), respectively; bn is rounded to the nearest greater integer.

The total number of boat days in a month is:

$$bd(t) = nr(t) / nd \tag{17}$$

bd is rounded to the nearest greater integer.

For each month, boat cost (c_b) is

$$c_b(t) = bn(t) \cdot bfix / 12 + bvar \cdot bd(t) \tag{18}$$

where *bfix* is the vessel fixed cost in \$/year, and *bvar* is the variable and crew cost in \$/day.

Fingerling cost (c_r) is

$$c_r(t) = 1000 \cdot stock \cdot sp \tag{19}$$

where *sp* is the fingerling cost in \$/fish. Feed cost (c_f) is

$$c_f(t) = fq(t) \cdot fp \tag{20}$$

where *fp* is the feed cost in \$/kg. Shore cost (c_s) is

$$c_s(t) = (sh + ins) / 12 \tag{21}$$

where *sh* is the on-shore cost (e.g., dock, facilities, management administration, marketing and distribution) in \$/year and *ins* is the insurance cost in \$/year.

From Equations (7), (9), and (18) through (21), we can calculate the total cost (*C*) in each month

$$C(t) = \sum_i c_i(t) \tag{22}$$

Note that *i* = [*k, m, b, r, f, s*].

<u>*Net Revenue*</u>

As noted, our model simulates monthly cash flow for a 15-year period and *t* = 1, 2, …, 180 (month). The cages are installed sequentially in the first 24 months. From (7), we define the present value of total investment as:

$$I = \sum_{t=1}^{24} \frac{c_k(t)}{(1+\delta/12)^t} \tag{23}$$

where δ is the annual discount rate (monthly discount rate is δ/12). The project's net present value may be computed using (6) and (22) as:

$$NPV = \sum_{t=1}^{180} \frac{R(t) - C(t)}{(1+\delta/12)^t} \tag{24}$$

Model Input Parameters

We apply the model described above to Atlantic cod and salmon, respectively. Cod can be stocked and harvested year round in southern New England waters. The grow-out site is located 6 km from the shore station or dock used by the support vessel. The water depth is 50 meters (m). Monthly water temperatures are shown in Table 6.1. Also included in Table

6.1 are the monthly average dockside prices for cod. These prices are based primarily on landed value reported by NOAA Fisheries. Biological data for the analysis are from Jobling (1988), Best (1995), and Bjorndal (1990). For specific functional forms, we model mortality in (2) as a function of fish weight (*w*):

$$m(\tau) = 0.01 - 0.000001w(\tau) \tag{25}$$

The above specification is based on experience with salmon farms as reported in Bjordal (1990).[5] According to Jobling (1988), the monthly growth in (3) is as a function of fish weight and water temperature:

$$g(\tau) = 0.37223w(\tau)^{0.559}e^{0.297\gamma - 0.000538\gamma^3} \tag{26}$$

where g is in grams per month, w is weight in grams, and γ is the temperature in degree Celsius.

Following Jobling (1988) and Best (1995), we specify FCR as a function of fish weight:

$$s(\tau) = [1.5 - 0.00035w(\tau)] / \psi \tag{27}$$

where $0.4 \le \psi \le 1.1$ is an adjustment factor that allows us to change the baseline FCR ($\psi = 1$) to simulate different feeding technologies.

Table 6.2 summarizes other model input parameters for cod describing the cage system, stocking, feed cost, boat, etc. These data are based on personal communications with cage manufacturers, industry experts, and Bjorndal (1990). As shown in the table, the cage capacity per cohort is 5,000 m^3. With a total of 24 cohorts and annual output of over 2,000 metric tons (mt), our simulated cage farm is larger than typical existing farms.[6] The baseline fixed cost for the grow-out support vessel, which stocks the cages, carries feed to the cages, supports maintenance, and carries out harvesting, is $100,000/year. Operating costs are $1,500 a day for fuel and other consumables, and personnel costs for a crew of four are another $1,500 per day. The vessel has an operating speed of 15 km/h and a payload capacity of 30 metric tons. On a typical round-trip carrying feed, it spends three hours on site. The maximum length of a work day is 14 hours and, due to weather constraints and maintenance requirements, the vessel is at sea a maximum of 25 days per month. On-shore costs include $30,000/year for dock use and other on-shore facilities, $70,000/year for management and administrative costs, and $50,000/year for marketing and distribution. The on-shore costs cover the salaries for one manager and two office staff. A set of high-end input values[7] is included in the last column for sensitivity analysis. According to Tveteras (2002a), production costs decline with respect to the industry scale in a regional operation (i.e., total employment, farm density, and output quantity).

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[5] In the study, salmon parameters are used where cod data are unavailable. It should be noted that the parameters for cod may be quite different from those for salmon.

[6] Existing studies have examined offshore farms with output ranging from 250 to 500 MT/year (Kam et al., 2003; Tveteras, 2002a; Posadas and Bridger, 2003; Bjorndal, 1990). The average output of 568 salmon farms in Norway was 277 mt/year (Tveteras, 2002a).

[7] Unit cage costs of $27/ m^3 and $50/$m^3$ have been reported by Kam et al. (2003) and Posadas and Bridger (2003), respectively, for cages size below 3,000 m^3. Labor cost may vary depending on both productivity (ranging from 30 to 500 MT fish per man-year) and wages ($30 – $60/man-year). For an assessment of labor productivity, see Forster (1999).

Environmental compliance costs are also included in the high-end cost inputs (see Table 6.2). These cost data are based on EPA (USEPA, 2002) estimates of four pollution control measures for offshore cage aquaculture: (i) Feed Management (*fmv* is the cost associated with extra time for record keeping); (ii) Solid Control BMP Plan (*scf* covers the cost associated with developing three 5-year plans, and *scv* is the cost for monthly review of the plans); (iii) Drug and Chemical Control BMP Plan (*dcf* is the cost to develop three 5-year plans, and *dcv* is the cost for monthly review of the plans); and (iv) Active Feed Monitoring (*aff* is the cost of one set of underwater cameras and *afv* is the cost associated with feeding control). These pollution control measures are cumulative and designed to lower feed and drug inputs. Note that *efix* in (7) is calculated using *scf*, *dcf*, and *aff*, and *evar* in (9) is based on *fmv*, *scv*, *dcv*, and *afv*.

For salmon, we consider the same production schedule and similar technology. Monthly growth is modeled as:

$$g(\tau) = 141 + 0.024w(\tau) \tag{28}$$

The FCR is:

$$s(\tau) = 1.5 - 0.00011w(\tau) \tag{29}$$

We specify a salmon price of $4/kg for base case simulation. Other baseline and high-end input parameters are summarized in Table 6.3. Note that the number of juvenile salmon stocked in each cohort is much smaller (45,000) than that of cod (150,000 in Table 6.2), as the size of juvenile salmon is large and also more costly.

Simulations and Results

Using the input parameters in Tables 6.1 and 6.2, we use the model[8] to simulate offshore cod production. For the baseline input parameters, an open-ocean cod farm requires an investment of $2.01 million to construct and the project's net present value (NPV) is $10.62 million (Table 6.4). Once fully installed, the farm produces cod year-round with an average production rate of 177 metric tons per month. Using the monthly farm-level feed quantity (*fq*) from (10) we estimate the average yearly feed quantity as 2,765 metric tons per year. The present value of total project cost in 15 years[9] is $35.87 million, or $2.39 million per year. The largest cost components are feed (41%) and fingerlings (40%). For the set of high-end costs (last column in Table 6.2), the offshore project is not economically feasible (NPV = -$13.38 million < 0). Using baseline costs, we calculate the NPV for different prices. As depicted in Figure 6.1, offshore cod farming is not economically feasible if the price is below $2/kg.

The simulation results for salmon are presented in Table 6.5. For the baseline input parameters in Tables 6.3 and at a harvest price of $4/kg, an offshore salmon farm generates a NPV of $29.49 million. The farm produces salmon year round with an average production

[8] All computer programs for the study are written in MATLAB.
[9] Including both investment and operating costs.

rate of 169 metric tons per month.[10] The average yearly feed quantity is 2,619 metric tons per year. The 15-year total project cost is $31.32 million ($2.09 million per year). As for cod production, the largest cost components are feed (55%) and fingerlings (24%). For high-end costs, the project NPV is reduced to $14.29 million. Again, we conduct a sensitivity analysis with respect to fish price, using baseline costs. The results indicate that offshore salmon farming is also not economically feasible if the price is below $2/kg (see Figure 6.2).

Given the importance of feed cost in offshore production, we examine the effect of different feed conversion ratios (FCR) on feed quantity and, in turn, on NPV for cod farming (see Figure 6.3).[11] As shown in the upper panel of the figure, cod aquaculture is economically feasible (NPV > 0) when average FCR is below 2.3. Efforts have been made by the aquaculture industry to lower FCR. For example, in the Norwegian salmon industry, FCR declined from close to 3 in 1980 to just over 1 in 2000 (Tveteras, 2002b). In lab experiments, it has been possible to achieve FCRs as low as 0.6 (Asche et al., 1999).[12]

Next, using the baseline input parameters for cod, we simulate the impact of rising feed cost on NPV. The results are illustrated in Figure 6.4. Also shown in the figure is the effect of a discount rate on NPV. As the feed cost approaches $1/kg, NPVs drop into the neighborhood of zero. As expected, for a fixed feed cost, NPV declines with a higher discount rate.

As noted, several key economic and biological variables in the model may be specified as stochastic. In this example, we attach a normally distributed random element, $\xi_j \sim N(0,\sigma_j^2)$, to each of the five variables: mortality rate (m), water temperature (γ), fish weight growth (g), fish price (p), and feed cost (fp). We run the stochastic version of the baseline cod model for two sets of variances, as Cases 1 and 2 shown in Table 6.6. For Case 1, the expected NPV is $10.81 million and the variance of project NPV is 6.37. For Case 2, the expected NPV is $11.83 million with a much larger variance of 33.88. The histograms of the random error terms attached to each of the five variables and resulting NPVs for Cases 1 and 2 are depicted in Figures 6.5 and 6.6, respectively. The figures show that for the set of smaller variances (Case 1), the NPV is always positive, while for the set of larger variances (Case 2), the left-side tail of the distribution clearly suggests the possibility of negative net returns.

When risk and uncertainty are present, the basic investment rule should be modified. Generally, a greater revenue stream will be required to justify the same level of investment. Although individuals have different attitudes toward risk, most are either risk neutral or slightly risk averse (see Kumbhakar, 2002; Eggert and Martinsson, 2004). For risk-averse investors, the investment rule is to invest if the value of the project is at least as large as the investment cost plus a risk premium.[13]

[10] Year-round stocking for salmon production may not be feasible in some locations (see Kite-Powell et al., 2003).
[11] Baseline costs were used for the simulation.
[12] FCRs vary among species and production systems and geography.
[13] For a discussion of risk and aquaculture, see Jin et al. (2005).

Finally, we examine the effect of distance from dock to grow-out site (distance to shore) on the economic feasibility of offshore aquaculture. Because most of the near-shore waters are heavily used for fishing and recreation, the most promising direction for aquaculture is far offshore, in open water relatively free of use conflicts and environmental contamination. Investment and production costs escalate as a cage farm is sited further offshore for two reasons. First, the cost of cage installation is proportional to water depth (Equation 8). In addition, vessel transportation costs are also positively related to distance. Two water depth profiles near Cape Cod are depicted in Figure 6.7. Apparently, growth in costs with respect to distance is greater to the north than to the south of Cape Cod, as water depth increases more rapidly in the north.

Again, we use the baseline cod model to illustrate how distance to shore affects boat operation and related costs.[14] In the study, we consider only vessel day trips and set the maximum distance at 25 nautical miles (46.3 km). A further increase in distance may significantly alter vessel operations and result in substantial cost escalations.

As shown in the upper section of Table 6.7, one 30-ton vessel operating 14 hours a day is capable of meeting the transportation need of an offshore cage farm located within 25 nautical miles. At the 5-nautical-mile location, the vessel can make two trips a day, lowering the total number of boat days in a month and related costs. The effect of increasing distance on vessel trips is more evident when vessel operation time is extended to 20 hours a day (see the middle section in the table). The vessel trip number declines from three per day at 5 nautical miles to one per day at 25 nautical miles. As a result, the total number of boat days per month rises from 7 to 19. To highlight the effect, we reduce the vessel payload to 5 tons in our simulation.[15] For the smaller vessel size (lower section in the table), we see an increase in vessel numbers from two to five as the distance to shore rises from 5 to 25 nautical miles. The related effect on costs is more drastic. In all three cases, the cost share for cage installation is relatively stable, suggesting a smaller effect of distance on investment cost than operating cost.

We plot the total 15-year project costs (in Table 6.7) with respect to distance to shore in Figure 6.8. The investment and production costs are influenced by vessel operation schedules. As noted, larger vessels carry more cargo and make fewer trips than smaller vessels. Longer vessel operation hours enable more trips in a day. Thus, the case with 5-ton vessels is more costly than that with a 30-ton vessel. For the same vessel (i.e., 30-ton), the total cost is lower if the vessel operation time is extended from 14 to 20 hour per day.

Conclusions

Open-ocean aquaculture is an emerging industry. Some technical, biological, and regulatory uncertainties surrounding open-ocean grow-out systems are now being resolved through publicly-sponsored demonstration projects and private sector start-ups. In this chapter, we develop a quantitative assessment of the economic feasibility of offshore aquaculture. The analytical framework is based on a firm-level investment-production model

[14] Water depth profile north of Cape Cod was used in the simulations.
[15] Boat costs were kept unchanged in the simulation, leading to a higher unit cost ($/payload ton).

that simulates individual grow-out projects and estimates the project's investment, cost shares, and NPV. We develop simulations of offshore aquaculture of Atlantic cod and salmon, respectively. The simulated production technologies are large offshore cage farms with annual output over 2,000 metric tons.

Both cod and salmon farming in offshore waters are shown to be economically feasible based on our baseline cost and revenue parameters. Offshore aquaculture may not be profitable if the price of fish is below \$2/kg (\$0.91/lb), feed cost is higher than \$1/kg, or the feed conversion ratio (FCR) is greater than 2. Costs of feed and juvenile fish account for over 70% of the total investment and operating costs. In the case of salmon, the share of feed cost is about 50%.

Offshore aquaculture may only be economically feasible in waters within 25 nautical miles. Further increases in offshore distance will significantly alter the vessel operation schedule and result in a substantial cost increase. Operating under risk and uncertainty, greater project revenues are needed to justify the elevated total cost of investment (for example, a firm's risk premium).

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Table 6.1. Monthly average temperatures and cod price by size.

Month	Water Temperature	Cod Price ($/kg)		
	C^0	Small	Medium	Large
Jan	2	2.70	3.14	3.57
Feb	2	2.64	3.14	3.48
Mar	3	2.59	3.09	3.43
Apr	5	2.21	2.63	2.91
May	10	2.31	2.75	3.05
Jun	17	2.31	2.75	3.05
Jul	21	2.23	2.65	2.94
Aug	22	2.55	3.04	3.37
Sept	22	2.49	2.96	3.29
Oct	18	2.54	3.03	3.36
Nov	10	2.33	2.78	3.08
Dec	5	2.60	3.10	3.44

Note: Cod size categories are: small (750 grams ≤ w < 1,130 grams); medium (1,130 grams ≤ w < 2,270 grams); and large (w ≥ 2270 grams). For w < 750 grams, the assumed price is zero.

Table 6.2. Model input parameters: cod.

Parameter	Description	Unit	Baseline Value	High-end Value
v	cage volume per cohort	m^3	5,000	5,000
acq	cage purchase cost [a]	$/m^3	15.00	25
inst	cage mooring and installation cost	$/m^3	3.00	3.00
cm	cage operating and maintenance cost [b]	$/m^3/year	1.00	6
stock	number of fingerlings stocked per cohort	1,000 fish	150	150
sg	stocking weight	gram/fish	50	50
φ	ratio of water weight to fingerling weight during transport to farm		5	5
sp	fingerling cost	$/fish	0.85	1.50
fp	feed cost	$/kg	0.60	0.73
bfix	vessel fixed cost	$/year	100,000	150,000
bvar	vessel variable and crew cost [c]	$day	3,000	3,000
ld	vessel payload	MT	30	30
trip	round trips per day		3	3
sh	on shore cost [d]	$/year	150,000	250,000
ins	insurance cost [e]	$/year	50,000	300,000
fmv	feed management variable cost	$/cohort/month	0	33.32
scf	solid control BMP plan fixed cost	$/farm	0	1615.20
scv	solid control BMP plan variable cost	$/month	0	21.15
dcf	drug and chemical control BMP plan fixed cost	$/farm	0	1615.20
dcv	drug and chemical control BMP plan variable cost	$/month	0	21.15
aff	active feed monitoring fixed cost	$/farm	0	10,000
afv	active feed monitoring fixed cost	$/cohort/month	0	33.32
δ	annual discount rate		0.07	0.07

Notes:
a. Including feeder and other equipment
b. Including fuel, utilities, diving, repair, etc.
c. Including 4 crews (average $25/hour)
d. Including salaries for 1 manager and 2 office staff
e. Insurance covers fish and other capital

Table 6.3. Model input parameters: salmon.

Parameter	Description	Unit	Baseline Value	Highe-end Value
v	cage volume per cohort	m^3	5,000	5,000
acq	cage purchase cost	$\$/m^3$	15.00	25
inst	cage mooring and installation cost [a]	$\$/m^3$	3.00	3.00
cm	cage operating and maintenance cost [b]	$\$/m^3$/year	1.00	6
stock	number of fingerlings stocked per cohort	1,000 fish	45	45
sg	stocking weight	gram/fish	150	150
φ	ratio of water weight to fingerling weight during transport to farm		5	5
sp	fingerling cost	$/fish	1.50	1.75
fp	feed cost	$/kg	0.73	0.9
bfix	vessel fixed cost	$/year	100,000	150,000
bvar	vessel variable and crew cost [c]	$day	3,000	3,000
ld	vessel payload	MT	30	30
trip	round trips per day		3	3
sh	on shore cost [d]	$/year	150,000	250,000
ins	insurance cost [e]	$/year	50,000	300,000
fmv	feed management variable cost	$/cohort/month	0	33.32
scf	solid control BMP plan fixed cost	$/farm	0	1615.20
scv	solid control BMP plan variable cost	$/month	0	21.15
dcf	drug and chemical control BMP plan fixed cost	$/farm	0	1615.20
dcv	drug and chemical control BMP plan variable cost	$/month	0	21.15
aff	active feed monitoring fixed cost	$/farm	0	10,000
afv	active feed monitoring fixed cost	$/cohort/month	0	33.32
δ	annual discount rate		0.07	0.07

Notes:
a. Including feeder and other equipments
b. Including fuel, utilities, diving, repair, etc.
c. Including 4 crews (average $25/hour)
d. Including salaries for 1 manager and 2 office staff
e. Insurance covers fish and other capital

Tables 6.4. Model results: cod.

Output Variable	Description	Unit	Baseline Value	High-end Value
NPV	net present value	$ million	10.620	-13.375
I	investment	$ million	2.010	3.139
X(T)	average fish harvest	metric ton/month	177	177
N(T)	average number of fish harvested	fish/month	120,535	120,535
W(T)	average harvest fish size	kg	1.47	1.47
$12 \cdot E[fq(t)]$	average feed quantity	metric ton/year	2,765	2,765
Project Cost	total cost	$ million	35.871	59.867
	average annual cost	$ million	2.391	3.991
Cost Share	cage installation	%	5.6	5.2
	cage maintenance	%	2.8	10.2
	boat and crew	%	6.0	4.4
	fingerlings	%	39.5	41.8
	feed	%	40.9	29.8
	onshore and other	%	5.2	8.5
	total	%	100	100

Tables 6.5. Model results: salmon.

Output Variable	Description	Unit	Baseline Value	High-end Value
NPV	net present value	$ million	29.486	14.289
I	investment	$ million	2.010	3.139
x(T)	average fish harvest	metric ton/month	169	169
n(T)	average number of fish harvested	fish/month	37,446	37,446
w(T)	average harvest fish size	kg	4.52	4.52
$12 \cdot E[fq(t)]$	average feed quantity	metric ton/year	2,619	2,619
Project Cost	total cost	$ million	31.315	46.512
	average annual cost	$ million	2.088	3.101
Cost Share	cage installation	%	6.4	6.7
	cage maintenance	%	3.2	13.2
	boat and crew	%	6.0	5.0
	fingerlings	%	24.0	18.8
	feed	%	54.5	45.3
	onshore and other	%	5.9	11.0
	total	%	100	100

Table 6.6. Stochastic variable specifications.

Variables	Stochastic Variables	Error Distributions	Case 1	Case 2
mortality rate (m)	$m\ exp(\xi_m)$	$\xi_m \sim N(0, \sigma_m^2)$	$\sigma_m^2 = 0.01$	$\sigma_m^2 = 0.051$
temperature (γ)	$\gamma + \xi_\gamma$	$\xi_\gamma \sim N(0, \sigma_\gamma^2)$	$\sigma_\gamma^2 = 0.1$	$\sigma_\gamma^2 = 0.5$
fish growth (g)	$g\ exp(\xi_g)$	$\xi_g \sim N(0, \sigma_g^2)$	$\sigma_g^2 = 0.01$	$\sigma_g^2 = 0.05$
fish price (p)	$p + \xi_p$	$\xi_p \sim N(0, \sigma_p^2)$	$\sigma_p^2 = 0.1$	$\sigma_p^2 = 0.5$
feed cost (fp)	$fp + \xi_{fp}$	$\xi_{fp} \sim N(0, \sigma_{fp}^2)$	$\sigma_{fp}^2 = 0.01$	$\sigma_{fp}^2 = 0.05$

Table 6.7. Distance to shore, vessel operations, and costs (cod) [a].

Distance to shore nautical miles (km)	5 (9.26)	10 (18.52)	15 (27.78)	20 (37.04)	25 (46.3)
Water depth (m)	22.86	45.72	76.20	106.68	152.4
Vessel operation: 14 hours per day; vessel payload: 30 ton					
Vessel number	1	1	1	1	1
Boat trip/day	2	1	1	1	1
Boat days/month [b]	10	19	19	19	19
NPV ($ million)	10.206	8.682	8.656	8.630	8.604
Total cost ($ million)	36.286	37.81	37.836	37.862	37.887
Cage installation (%)	5.30	5.37	5.45	5.52	5.59
Boat and crew (%)	7.32	10.99	10.98	10.98	10.97
Vessel operation: 20 hours per day; vessel payload: 30 ton					
Vessel number	1	1	1	1	1
Boat trip/day	3	2	2	2	1
Boat days/month [b]	7	10	10	10	19
NPV ($ million)	10.706	10.180	10.155	10.129	8.604
Total cost ($ million)	35.785	36.311	36.337	36.363	37.887
Cage installation (%)	5.38	5.45	5.52	5.59	5.66
Boat and crew (%)	6.03	7.32	7.31	7.31	10.97
Vessel operation: 20 hours per day; vessel payload: 5 *ton*					
Vessel number	2	3	3	3	5
Boat trip/day	3	2	2	2	1
Boat days/month [b]	38	57	57	57	114
NPV ($ million)	5.403	2.140	2.114	2.089	-8.175
Total cost ($ million)	41.089	44.352	44.377	44.403	54.667
Cage installation (%)	4.68	4.75	4.81	4.87	4.93
Boat and crew (%)	18.16	24.12	24.11	24.09	38.30

Notes:
a. Loading time = 2 hours/vessel; Unloading time = 3 hours/vessel; Vessel speed = 15 km/hour; and Maximum boat days per month = 25 days
b. Total number of days of all vessels

Figure 6.1. NPV by price: cod.

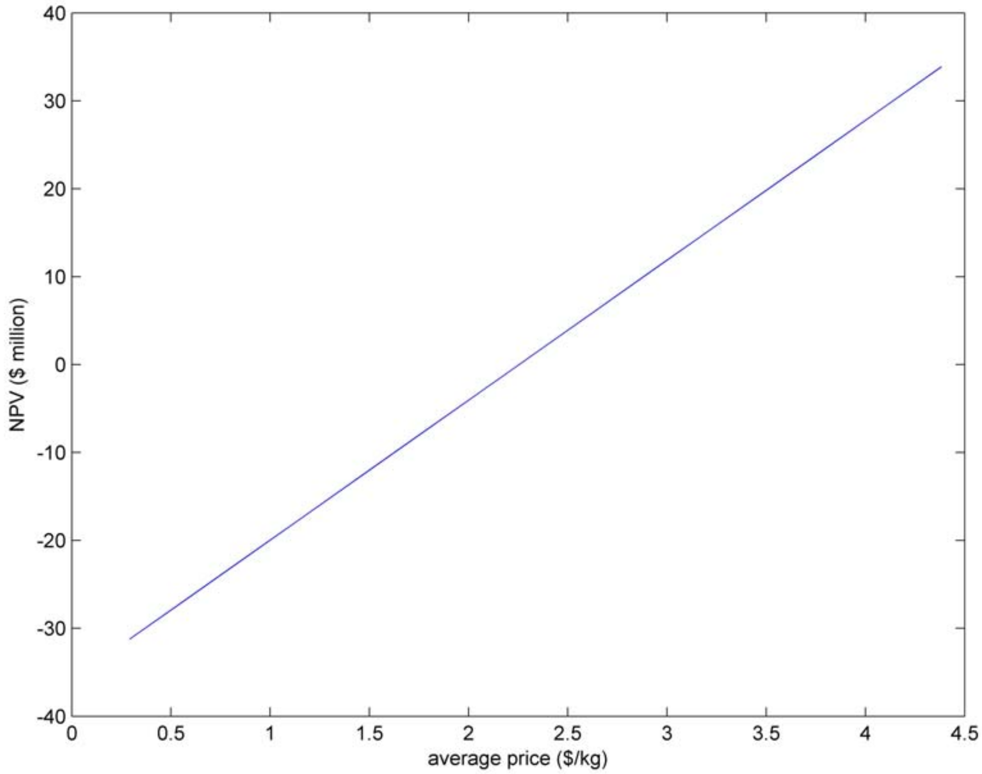


Figure 6.2. NPV by price: salmon.

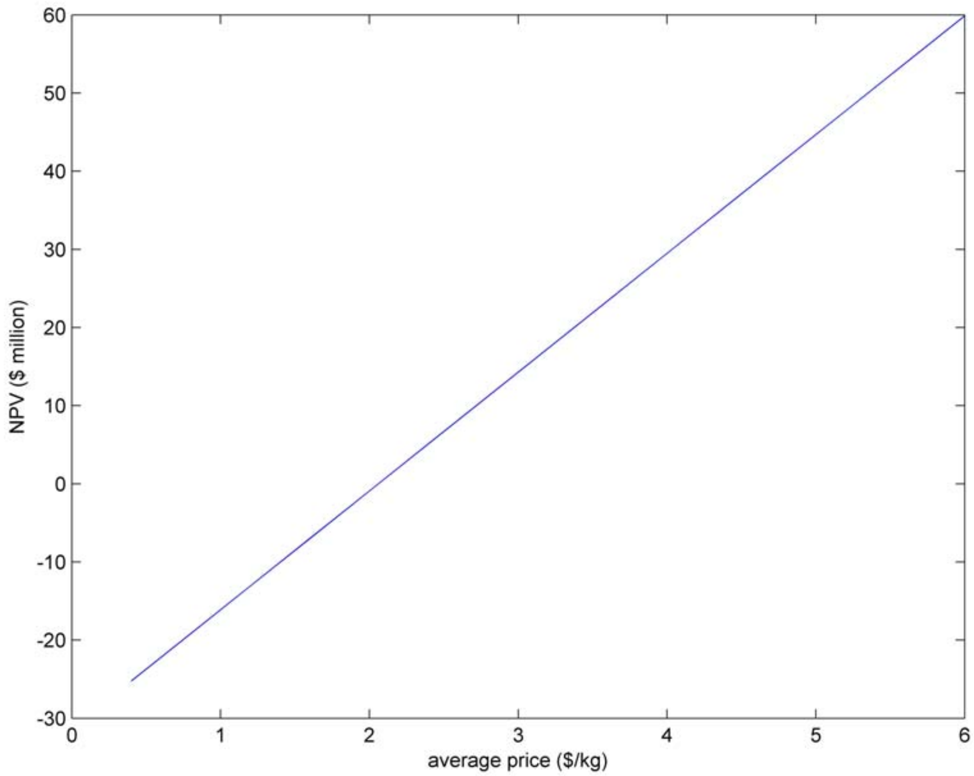


Figure 6.3. NPV and feed quantity by FCR (cod).

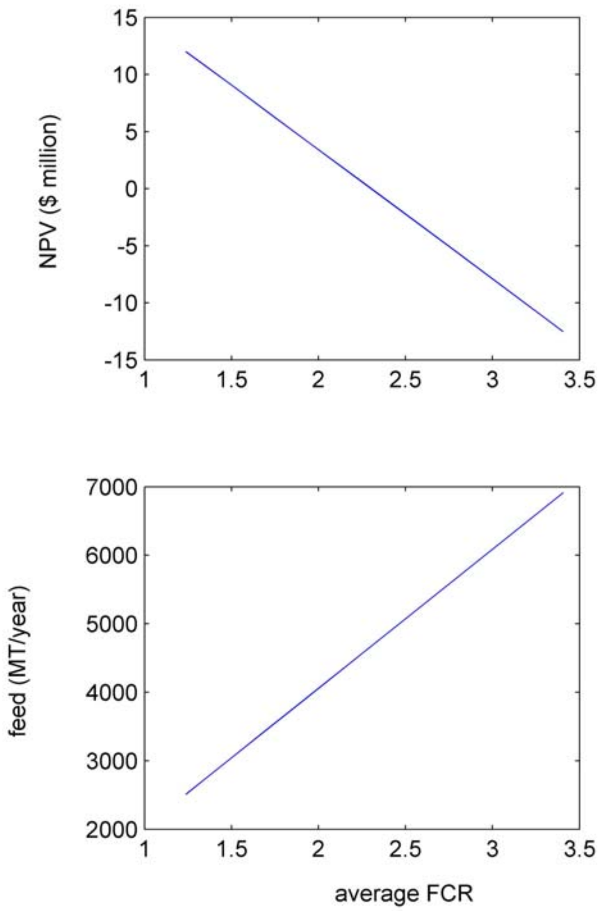


Figure 6.4. NPV by feed cost and discount rate (cod).

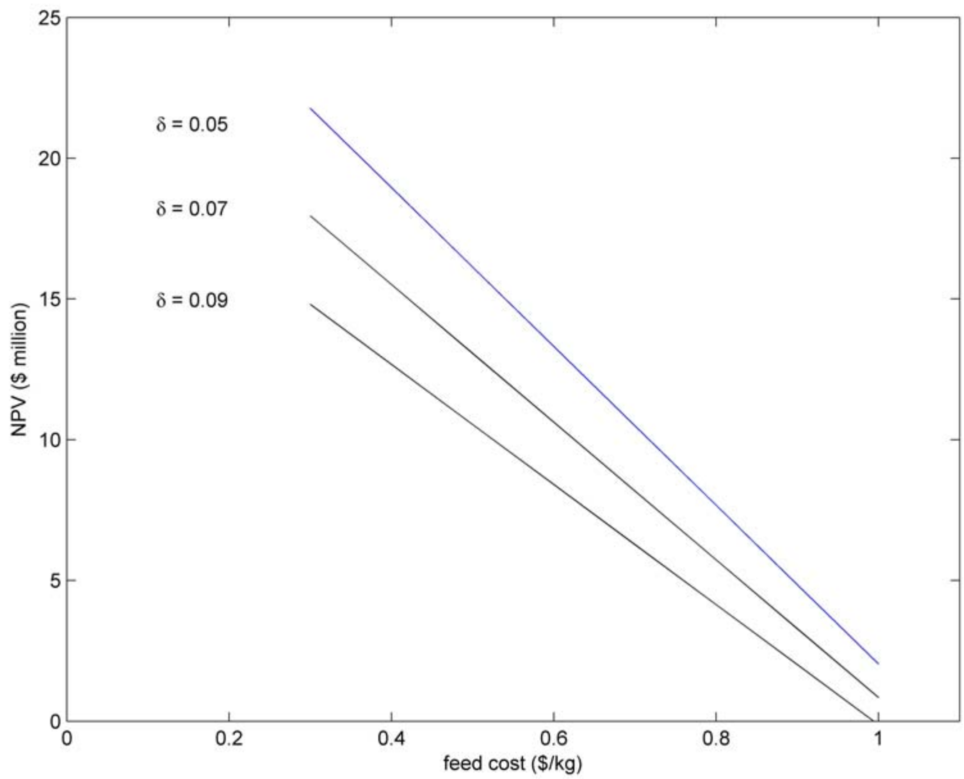
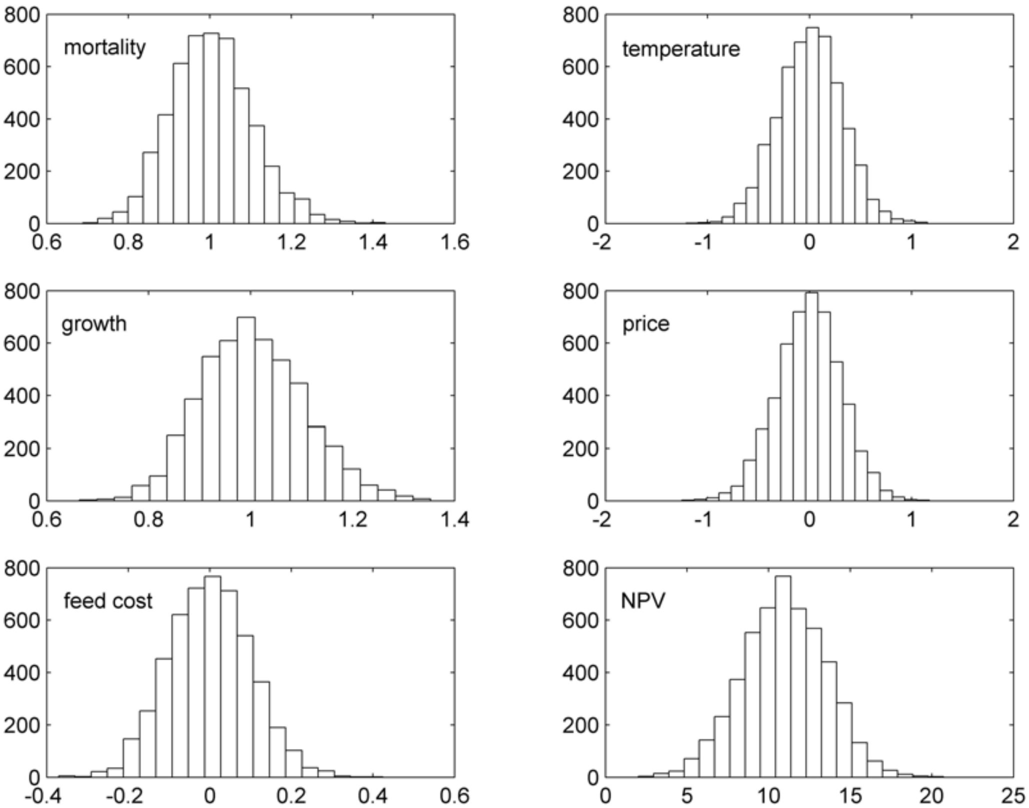
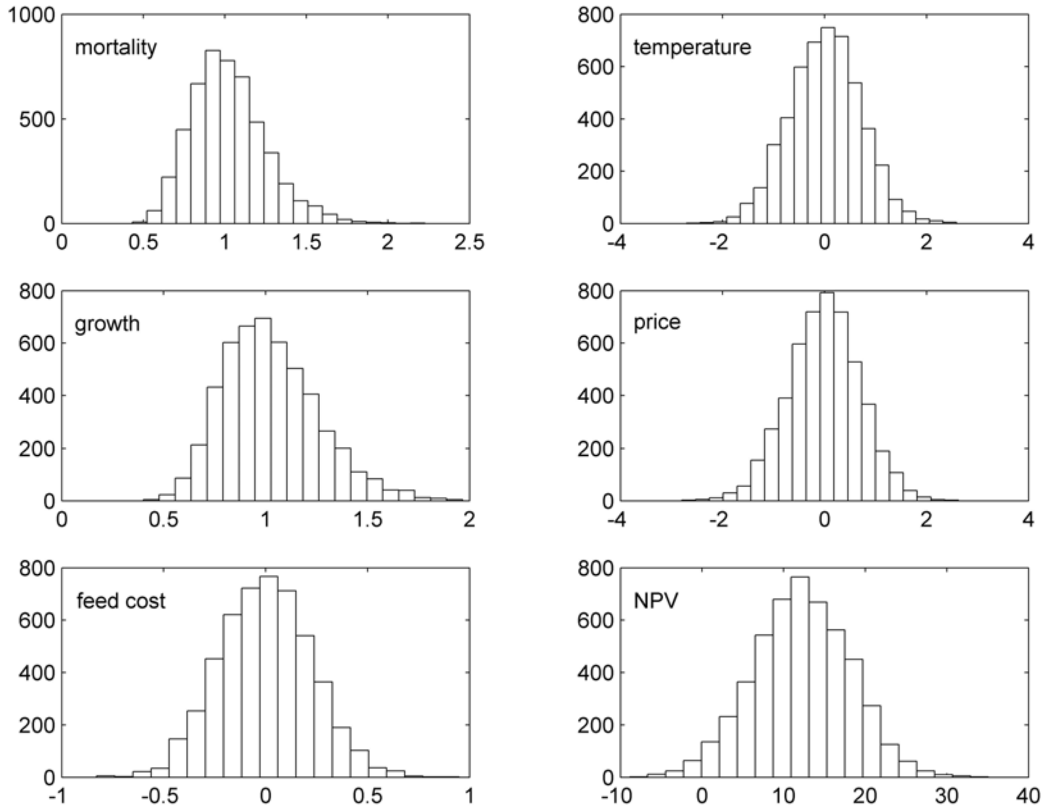


Figure 6.5. Histograms of NPV and errors associated with key parameters (case 1).



Notes: As specified in Table 6.4, the error distributions shown above are $exp(\xi_m)$ for mortality, ξ_γ for temperature, $exp(\xi_g)$ for fish weight growth, ξ_p for fish price, and ξ_{fp} for feed cost. Number of iterations = 5,000.

Figure 6.6. Histograms of NPV and errors associated with key parameters (case 2).



Notes: As specified in Table 6.4, the error distributions shown above are *exp*(ξ_m) for mortality, ξ_γ for temperature, *exp*(ξ_g) for fish weight growth, ξ_p for fish price, and ξ_{fp} for feed cost. Number of iterations = 5,000.

Figure 6.7. Water depth by distance to shore.

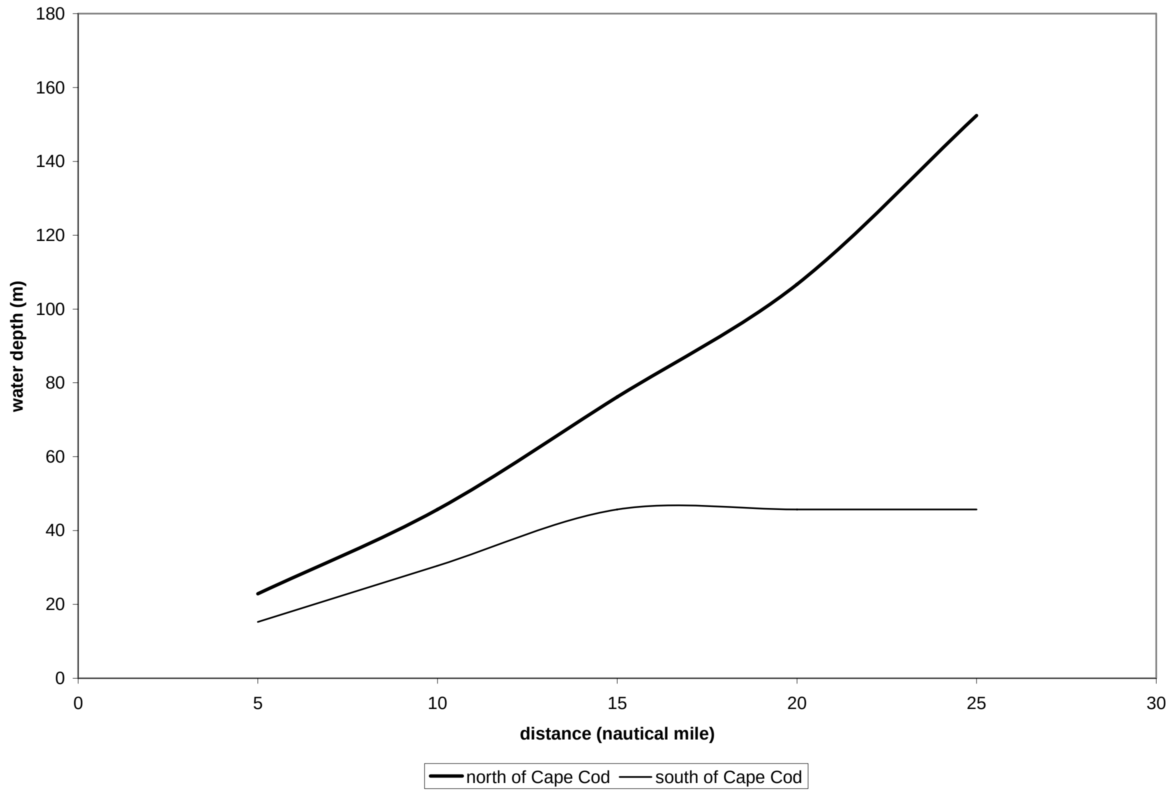


Figure 6.8. Total cost by distance to shore (cod).